Detection of Earth in the Presence of Stellar Noise

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Overview

- We apply a dynamic starspot model to estimate the impact of starspot noise on the detection of Earth via astrometric and radial velocity techniques.
- We find that for the Earth-Sun system, starspots
  - do not appreciably interfere with astrometric detection.
  - impose severe requirements on the number of measurements and duration of an observing campaign needed for radial velocity detection.

Dynamic starspot model

- Assumptions
  - All of the Sun's visible flux variation is due to dark starspots.
  - On average there are three starspots of equal area on the Sun's surface at any time.
  - The birth of starspots is a Poisson process in time.
- Adjustable parameters:
  - Lognormal distribution of starspot lifetimes (2 parameters)
  - Starspot area (1 parameter)
- Model includes effects of
  - Area projection and limb-darkening
  - Systematic latitude drift with solar cycle "Maunder Butterfly pattern"
  - Inclination of stellar rotation axis with respect to the line of sight.
- Each starspot is specified by its creation date, lifetime, latitude, and area.
- Each starspot is propagated in time as the star rotates.
- Drive the total daily starspot area with the 30-year record of sunspot numbers, that overlaps the space-based TSI (total solar irradiance) record.
- Tune the model parameters to approximately match the Sun's observed flux variations.

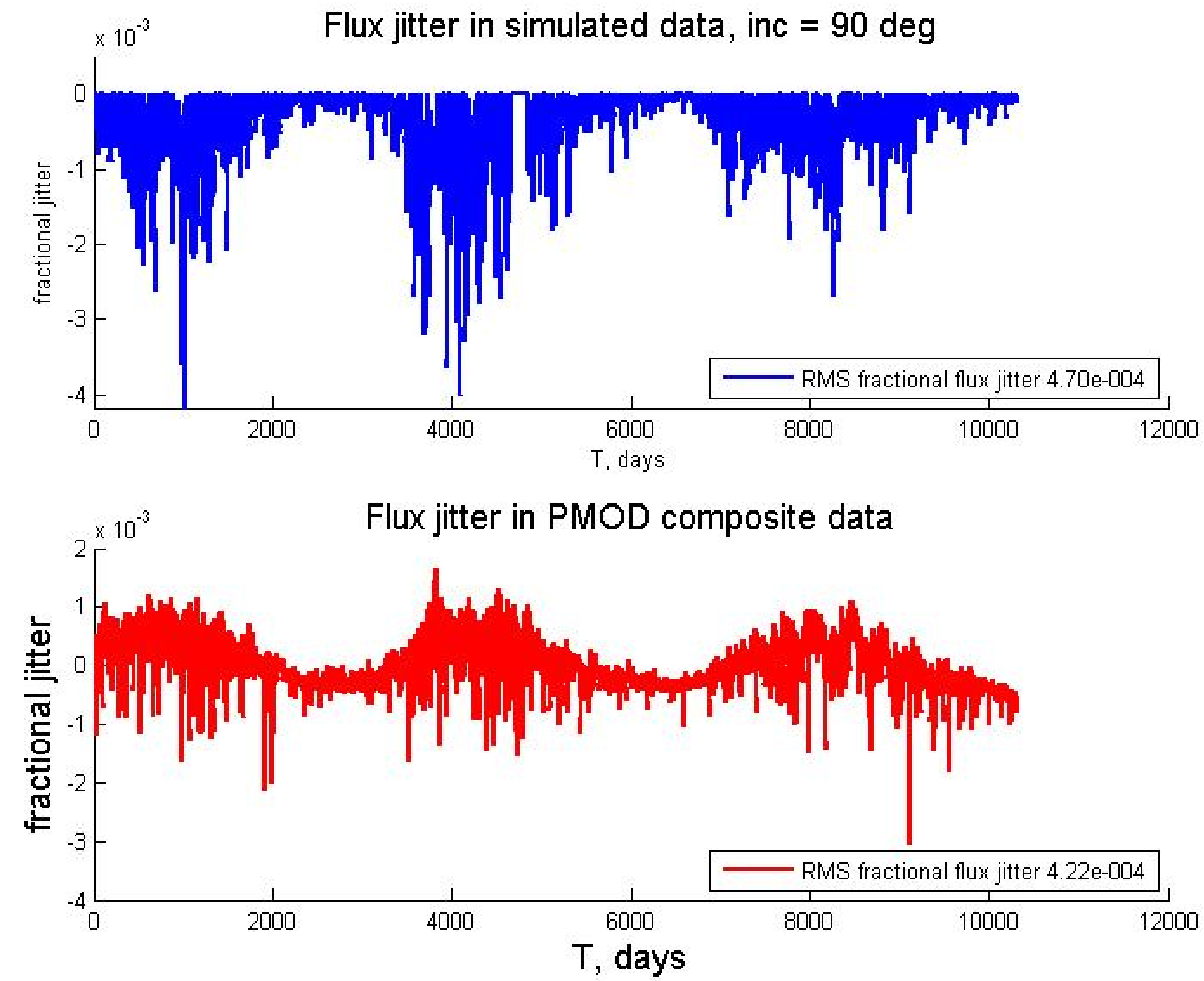
Flux jitter in the time domain

Simulation

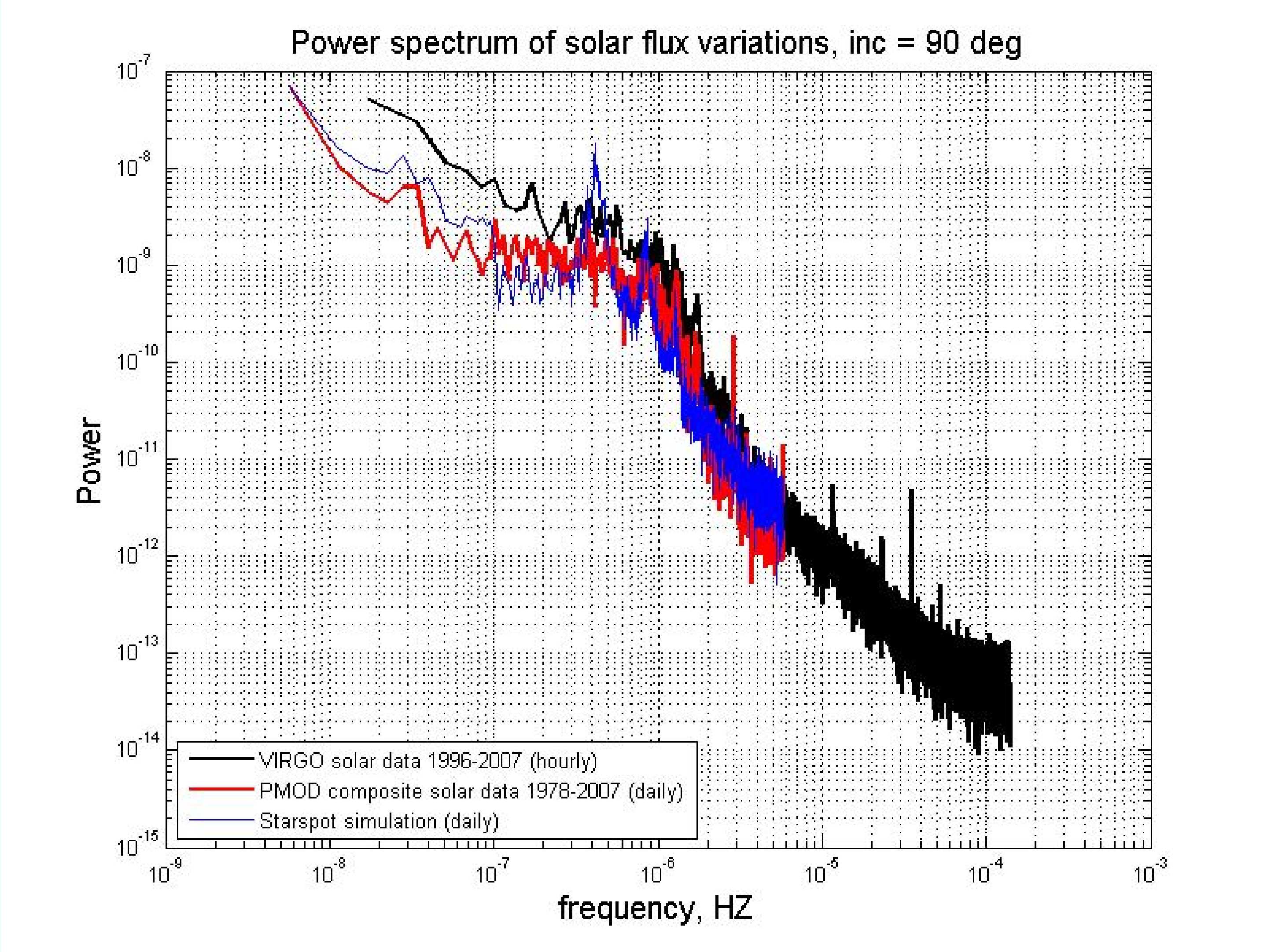
RMS = 4.7×10^{-4}

Observation

RMS = 4.2×10^{-4}



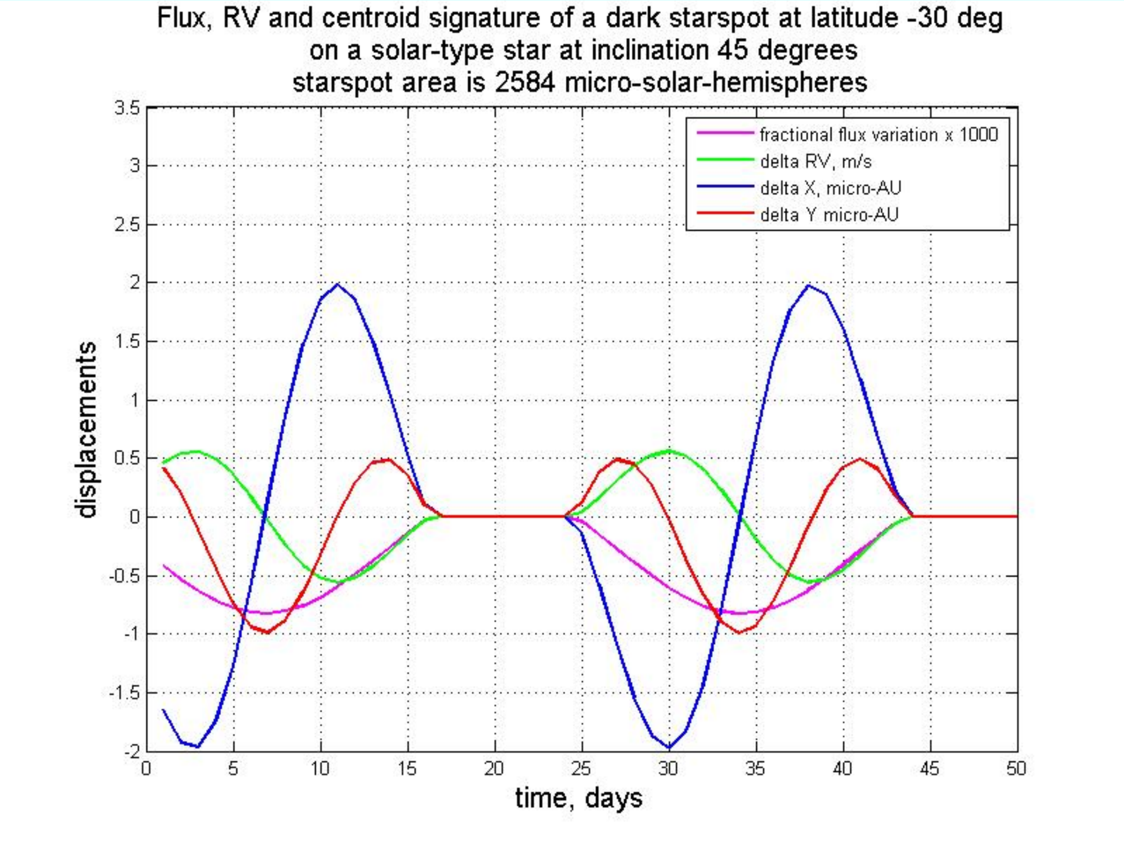
Flux jitter in the frequency domain



The simulation matches the observational data fairly well.

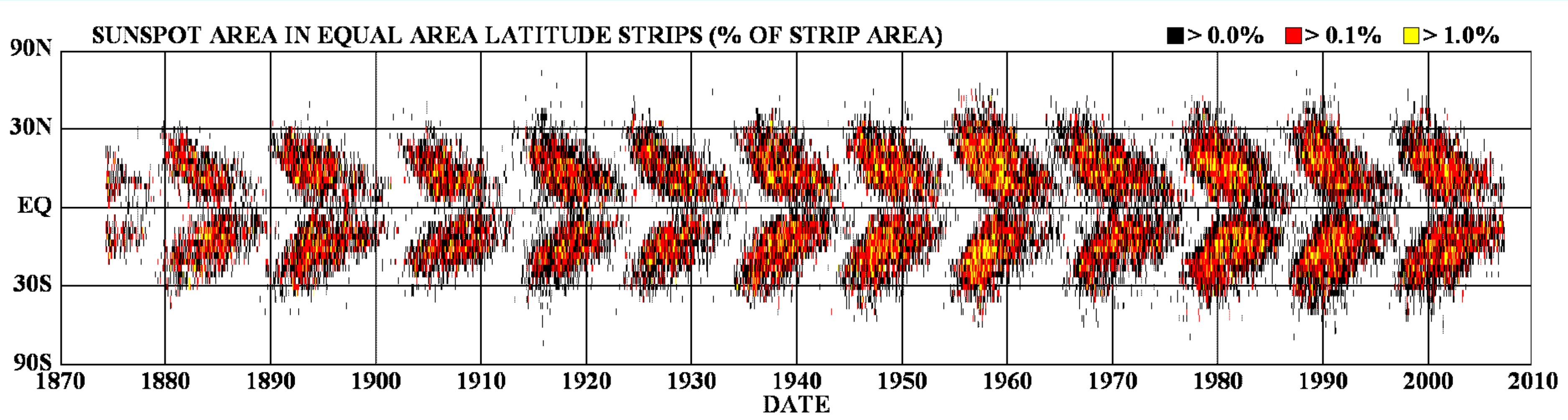
Starspots cause systematic variation of stellar flux, astrometric centroid and RV

- The effect depends on inclination and latitude.
- In the tangent plane: X is along the direction of the line of nodes, Y is along the projected direction of the star's rotation axis.
- In general, the jitter in the X centroid and RV are zero-mean, but the jitter in the Y centroid is not.
- The bias in the Y centroid is worst for the case of 45° inclination.
- ***Typical starspot lifetimes* are about a week so (roughly speaking) starspot noise***
  - ***Is correlated for measurements separated by less than a week.***
  - ***Is independent for measurements separated by over a week.***



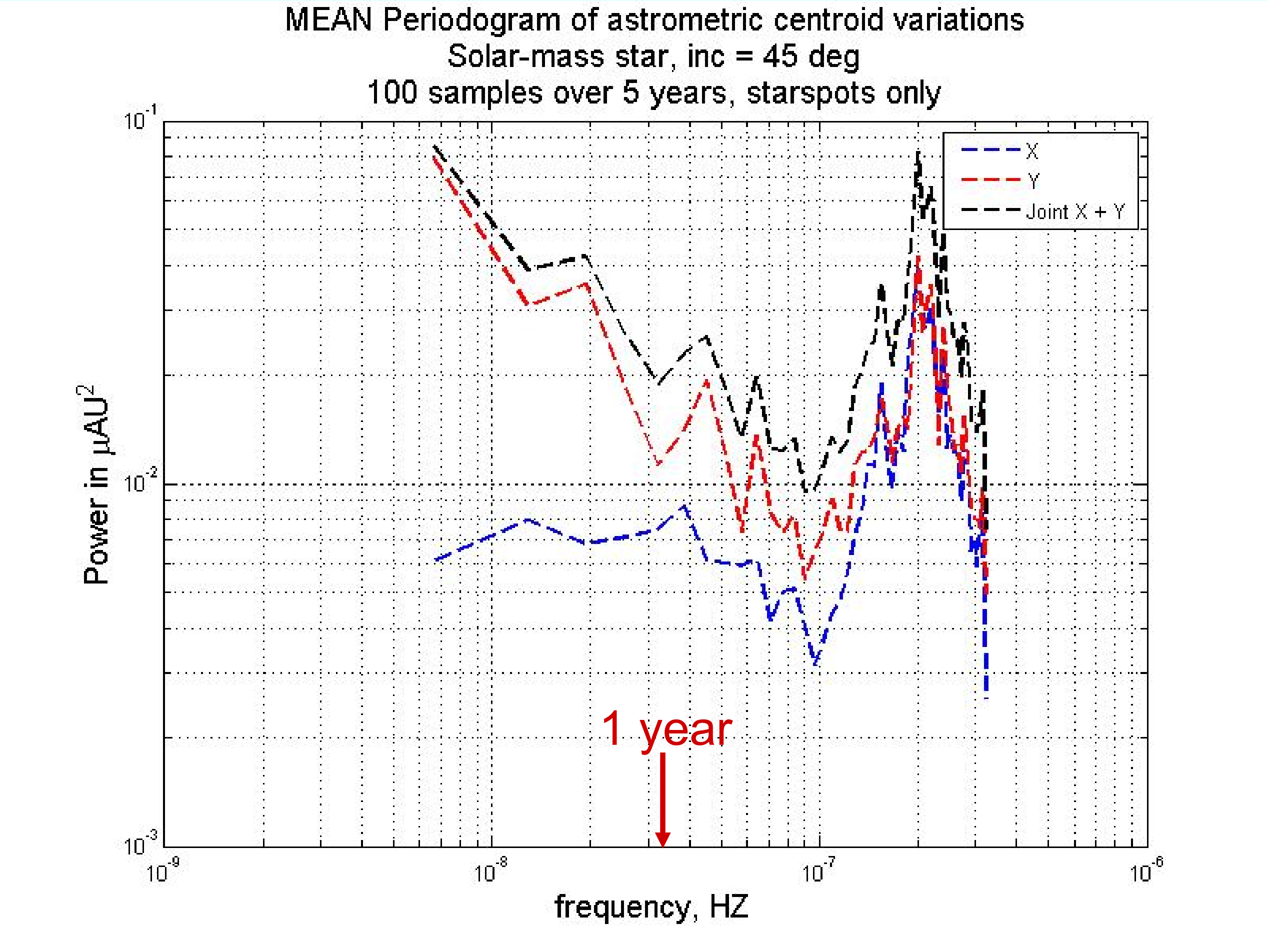
*The starspot represented in the figure above is persistent, for the purpose of illustration only.

Maunder Butterfly Pattern



- An 11-year sunspot cycle is included in the simulation.
- Sunspots occur at higher latitudes at the beginning of the cycle.
- As the cycle progresses sunspots become more likely to appear at lower latitudes.

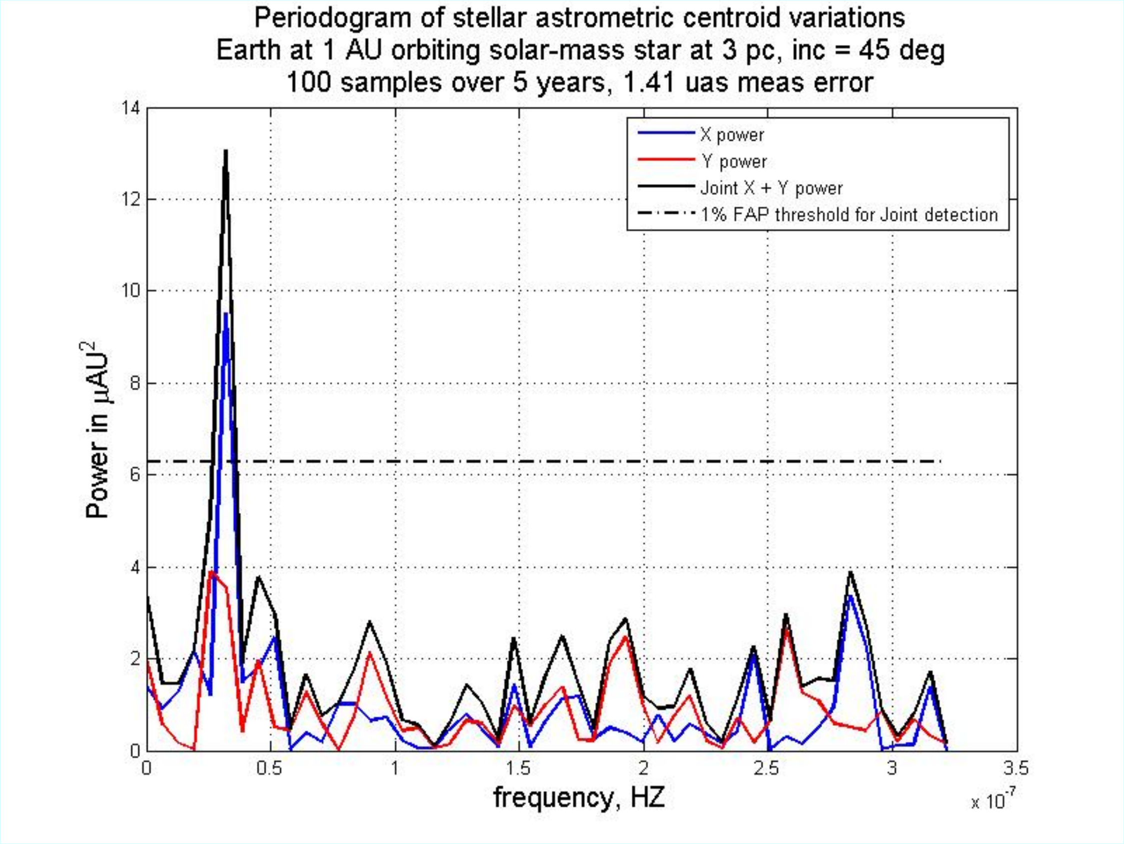
Power spectrum of centroid jitter due to starspots, 45° inclination



- Mean of 80 periodograms sampled 100 times over 5 years, as in a typical observing campaign.
- Captures noise in the astrometric centroid as a function of frequency; it is between 0.5 & 2 μAU per measurement.
- At a 1 year period, it's about 0.7 μAU per measurement.

- X jitter spectrum is fairly flat for periods longer than a few months.
- Y jitter increases at longer periods, due to starspot cycle systematics; but this is offset by the planet signal, which increases by about the same factor.

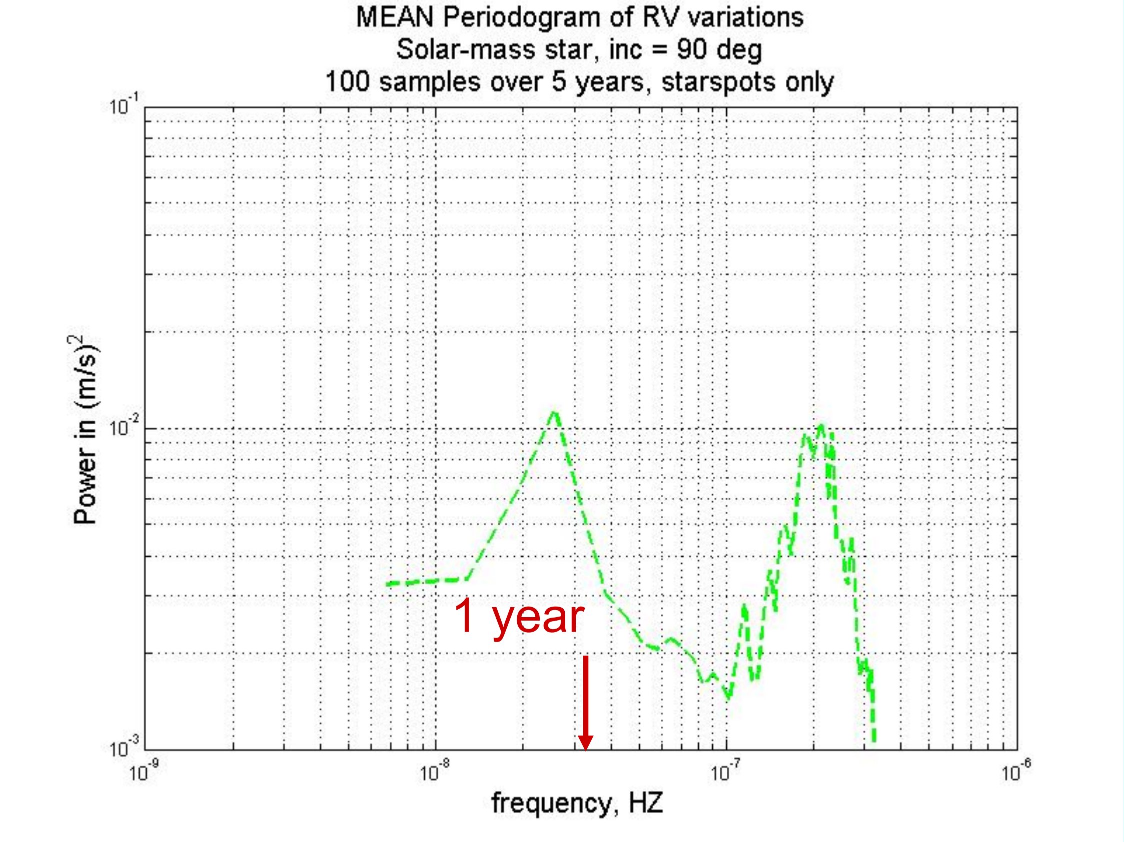
Astrometric detection of Earth at 3 pc in sunspot noise, 45° inclination



- Earth's signal is 3 μAU
- Starspot noise is 0.7 μAU per measurement.
- Instrument noise is 3 μAU per measurement, at 3 pc.
- Instrument noise <u>floor</u>
  - SIM PlanetQuest:
    0.025 μas, or
    0.075 μAU at 3 pc
  - SIM PlanetQuest Light:
    0.038 μas, or
    0.113 μAU at 3 pc
- SNR = 3*sqrt(100)/4.2 ~ 7

- ***At distances of 3 pc and beyond, instrument noise dominates starspot noise, so that***
  - ***Starspot noise doesn't interfere with astrometric detection of Earth (see periodogram, above).***
  - ***Even correlated starspot noise is generally not problematic: the noise average for groups of 10 or so measurements taken within a week is well above the starspot noise.***
- ***SIM PlanetQuest (or SIM PlanetQuest Light) could detect a 0.3 Earth mass planet in the habitable zone at 3 pc, with the 1000 measurements allowed by the noise floor.***

Power spectrum of RV jitter due to starspots, 90° inclination (edge-on)



- Mean of 80 periodograms sampled 100 times over 5 years, as in a typical observing campaign.
- Captures RV jitter due to starspots as a function of frequency: it's between 0.3 and 0.7 m/sec per measurement.
- At 1 year period, RV jitter is 0.6 m/sec per measurement

- ***Starspot noise is comparable to typical instrument noise of 1 m/sec.***
- ***RV signal of Earth is 0.09 m/sec, much smaller than starspot and instrument noise.***
- ***If the noise were to average down like root N, it would take over 8000 independent measurements at a precision of 1 m/sec to detect Earth with the same SNR (~7) as for astrometric detection.***
- ***But adjacent measurements would need to be spaced a week apart, otherwise their noise would be correlated, they would not be independent, and so could not not average down to below 0.6 m/sec***

Conclusion

- Astrometric starspot noise
  - Is small compared to Earth’s astrometric signature.
  - Is small compared to SIM PQ & PQ-light’s instrument noise.
  - Doesn’t interfere with astrometric detection of Earth.
- On the other hand, RV starspot noise correlations make RV detection of Earth extremely difficult.
  - Requires over 2000 measurements even at precision of 0 m/s.
  - Sampling rate must be lower than 1 per week to avoid correlations.
  - Such an observing campaign would take over 40 years.

Ongoing work

- We are currently extending this study to estimate the effect of starspots on the detection of potentially habitable planets around all the stars in the SIM target list. We will
  - Use existing space-based photometric time series from WIRE, MOST, and Hipparcos to study the flux variability of other main-sequence stars.
  - Exploit connections among flux variability, chromospheric activity (from Ca II H&K indices), age and rotation rate to extend our starspot model to other spectroscopic types on the main sequence.